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LIGHTING RECOMMENDATIONS AS INPUT TO COST-BENEFIT CALCULATIONS

Robert Clear and Sam Berman

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

A cost-benefit analysis based on visual-performance models is derived by considering the current consensus lighting recommendations, RQQ #6, as implicit estimates of cost-effective lighting. There is only partial consistency between models and these recommendations. The consistency analysis provides a quantitative basis for these recommendations, delineates their limits of applicability, and suggests changes in them for handling low reflectance tasks, aged workers, high electrical costs, or conditions where high visual speed and accuracy are very valuable.

Introduction

This paper focuses on office productivity, although many of the general comments apply to other lighting situations. The present IES office light level recommendations, RQQ #6, are based on a consensus procedure.[1] We will be referring to the IES recommendations frequently, so we have included a summary of the pertinent points in an appendix. As a stand-alone document there is no way to judge whether RQQ #6 gives cost-effective lighting, or is even consistent with the basic features of visibility models. However, the consensus procedure captures the experience of what works, and what does not, what is considered too expensive, and what factors are relevant to design. It therefore is a rough empirical estimate of cost effectiveness. In the consensus process individual estimates of the appropriate light level varied by as much as 50:1 for any given task. Because the final consensus value is not the product of an explicit cost-benefit analysis it is subject to errors and biases which diminish its credibility.

We do a cost-benefit analysis using a simple productivity model, and attempt to find values of the unknowns that are both physically reasonable, and consistent with the RQQ #6 estimates. The procedure is a cross-fertilization of theory and practical experience. The RQQ #6 values provide a method of specifying any unknowns in the cost-benefit framework, while the analytical framework provides a method of checking the internal consistency and thus the reasonableness of the recommended levels. Particular issues are whether the recommendations properly accounted for life-cycle costs, whether all important factors were considered, and whether there might have been confusion about the definitions and uses of some of the factors.

The precise numerical results obtained are obviously model dependent. However some of these appear very robust, and provide insight into the applicability of the RQQ #6 recommendations, especially for low reflectances and older workers. In the future, additional models will be tested to get a better idea of the sensitivity of the results. Our view is that coupling visual performance studies with field experience in a cost-benefit model provides insights for both theory and practice, and is a good first step towards analytically defensible, and cost-effective, recommendations.

Background

The basic idea behind cost-benefit analysis is to identify all the consequences of a given action and to assign monetary values to them so the action can be evaluated as an investment. Reducing everything to economic values, assuming it is possible, solves the problem of comparing guavas and tamarinds.

When past recommendations and practices are viewed in terms of costs and benefits it becomes clear that lighting has been responsive to implicit empirical judgements of cost-effectiveness. The rising footcandle levels in the early part of the century represent a period when the cost of delivering light was falling. The (temporary) inclusion of ESI (Equivalent Spherical Illumination) in recommendations reflects the influence of changes in ideas about benefits (quality). More recent history has seen rising operating costs, and falling light levels. Government lighting regulations can be viewed as a response to perceived societal costs that were "hidden" from the designer due to market imperfections. Cost-benefit analysis provides a framework for understanding the above history.

The issue of government regulations is not past history. Many IES members have publicly expressed their feeling that regulations are so restrictive that they do not permit good lighting and unduely restrict artistic freedom. In cost-benefit language the claim is that the regulations underestimate net lighting benefits. To the extent that the costs and benefits can be quantified, this disagreement can be restated in more objective economic terms. In cases where the disagreement is an objection to the constraints caused by the use of average values applied to a specific situation, the cost-benefit method could be used to build more flexible regulations, or uniform exception procedures.

Fundamental to a cost-benefit analysis is the ability to estimate costs and benefits. Costs tend to be closely related to light and power levels, which is probably one of the main reasons for the popularity of these factors in government regulations. As long as the specified light or power levels are adjusted to account for the factors that affect visual performance in commercial areas, these regulations can give cost-effective lighting. Light level, task size, contrast and glare have been known for a long time to be the four major factors affecting visibility.[2] Unfortunately, our understanding of exactly how these factors affect performance in terms of traffic safety, merchandising, or office productivity, is imperfect. Visual performance models have been developed, but they are often controversial and are either very restricted in their applicability, or have variable parameters whose values are not known for most situations of interest.[3,4,5] In short, we know the general trends, but not all the details.

The cost-benefit model

The goal of this cost-benefit analysis is to parameterize the costs and benefits in terms of a single independent variable, light level, and then determine the most cost-effective value of the independent parameter. The cost-benefit analysis can be performed either as a net-benefit calculation, or a cost-benefit ratio.

The first stage of our analysis uses the net-benefit calculation to determine the light level, E_o, with the maximum net-benefit. As light levels rise the incremental cost of light eventually becomes greater than the incremental benefits. Thus E_o can be directly computed from the requirement that the slope of the net-benefit curve versus light-level at E_o be equal to zero. This procedure allows us to find the approximate range for unknowns that are consistent with the RQQ recommendations. In the second stage of our analysis, we compute net benefits at different light levels, and compared the maximum value to the value at the RQQ #6 recommended light level. The rate of return for any differences is computed to test whether an investment was worthwhile, in addition to seeing whether the net-benefit difference was significant (large).

A convenient unit for the cost-benefit equation that is consistent with the units used for lighting recommendations is dollars/(time * area). The asterisk indicates multiplication. We let time = year and area = m^2 so that our basic net-benefit equation is:

$$\text{Net Benefit } (\$/(m^2\text{-year})) = \text{Benefits} - \text{Costs}. \tag{1}$$

The benefits and costs that we have identified for office lighting are the following:

$$\text{Benefits} = \text{Productivity} + \text{Heating} + \text{Comfort} + \text{Satisfaction}, \tag{2}$$

and,

$$\text{Costs} = \text{Capital} + \text{Electrical} + \text{Maintenance} + \text{Cooling}. \tag{3}$$

The RQQ #6 lighting recommendations explicitly refer to productivity as being the basis for the specified levels, and most of our focus in this paper is on modeling this term. Roadway and merchandising lighting will have other costs such as light trespass, and benefits, such as traffic safety and merchandisability, which need to be modeled.

The degree of detail needed for the analysis of each of the factors in the above equations depends upon the relative importance of each factor, and the aim of the overall analysis. For example, a designer comparing two designs knows the types of fixtures, and their costs and wattages. Given the electrical rate structure, an estimate for the hours of use, and the client's discount rate, the designer can estimate the economic consequences of heating, cooling, electrical load, and so on. At this level there is a great deal of both detail and flexibility, and the analysis is done against actual design options instead of against a parameter. Designers can even include factors such as owner occupied versus rental, in judging the economic life of fixtures and their relative cost effectiveness.

The RQQ #6 recommendations are meant to apply over a wide variety of conditions. Our analysis is perforce similarly general and all cost estimates are made in terms of light level. We assume that good practice implies reasonably high efficiencies so that more light means more watts and higher fixture costs. In this case costs will vary almost linearly with light level. In addition, we are assuming that the balance of heating versus cooling is approximately linear. All the linear terms are lumped into a single term proportional to the light level, E. Again we emphasize that this is a simplified general calculation, it is not exact for any individual design. Our cost function does not compensate for the fact that designers usually change light levels only in discrete steps, not continuously, nor does it account for any other variations from linearity that might occur.

The actual analysis tries a number of values for the net cost proportion, c ($c * E$ = costs - heating value). We estimated that the likely range for c was from one to four cents per lumen-year by noting that typical operation hours range from 2500 to 3500 hours/year, electrical charges range from typically from 2 to 15 cents/kWh, and so on for ten other factors.[1,6] Our estimates are consistent with another recent estimate for c.[7] We have not considered daylighting costs, and by inference, their effects on optimal electric light levels.

The RQQ #6 recommendations do not explicitly consider comfort or satisfaction. We assume that these factors are not sensitive functions of light level or task difficulty, and have not included them in our analysis. We want to emphasize, however, that they are legitimate factors for a cost benefit analysis. Comfort and satisfaction affect motivation and job desirability, and thus ultimately, can be traded off against salary.

At this time we know of no explicit attempts to put an economic value on these factors, although the proportion of people who will be comfortable, at least, can be roughly quantified via the calculation of visual comfort probability (VCP). At present these two factors probably have to estimated by looking at the market. A designer, for instance, could compare a preferred design against a poorer design and estimate the values of comfort and satisfaction from the differences in the cost-benefit analyses done without consideration of these factors.

Productivity and visibility

Our approach to the estimation of the effect of lighting variables on productivity is to separate the problem into two steps: 1) the estimation of visibility and visual performance from the lighting, worker age, and so on, and 2) the subsequent estimation of productivity from the visibility or visual performance. One approach to the first step is to estimate visibility in terms of contrast ratios with detection or resolution thresholds (VL), and then fit visual performance, defined as a mix of speed and accuracy, as a function of the visibility (VL).[3] A different model proposed by Rea estimates performance directly from luminance, contrast, and a threshold estimate, without an intermediate visibility parameter.[4]

The Rea model has been fit to only a single visual performance experiment over luminances from 12 to 170 cd/m^2, and the fit fails outside this range. The range we are interested in, is from 50 to 5000 cd/m^2, so these fits are not suitable for our cost-benefit analysis.

A simplified constant parameter version of Rea's model eliminates the problem extrapolations, but leads to a model which becomes a VL model in the limit of maximum relative performance. A partial confirmation of the validity of this simplification is that we found that a simple Ln(VL) Gaussian fit to Rea's data is almost as good as Rea's full model. We analyze a VL model, but since we expect the IES recommendations to apply to fairly high visual performance levels the results should be similar to a fit of the simplified version of Rea's model. We hope to analyze this simplified model, and other models, in the future.

To calculate VL we use a simplified version of the CIE 19/2 formula with a task size, d, of four minutes, a fixed eccentricity, $\tilde{x}$, of zero, and with modified age correction factors to eliminate unwarranted complexity.[3,8] The CIE 19/2 luminance correction factors, s and t, were combined into the function LM, with $\mathrm{Log}_{10}(\mathrm{LM}) = 0.07 - 0.009*(\mathrm{age}-20)$. The contrast correction factor, m_1, was fit as a simple interpolation between data points.[9] These modifications do not reduce predictive power.[8,10] Our VL equation is:

$$\mathrm{VL}(\mathrm{age},\mathrm{CRF},E) = a * \mathrm{CRF} * (\tilde{C}/m_1) * [\{b * \text{❹} * \mathrm{LM}/(\rho * E)\}^{0.4} + 1]^{-2.5} \qquad (4)$$

where CRF is the contrast rendering factor, E is the illuminance in lux, a and b are constants: a = 16.847, and b = 1.639, $\tilde{C}$ is the equivalent contrast (listed under task difficulty in RQQ #6), ρ is reflectivity, and LM and m_1 were defined above.

CIE 19/2 gives the effect of size on the shape of VL - luminance curve, but not on $\tilde{C}$✎ Adrian has a true size-luminance function, but his data extends only to 100 cd/m^2, and his fits do not extrapolate well to higher luminances.[11] Adrian's size dependency can be fit to the CIE data, and we expect to analyze the effect of size in the future.[8]

To use the RQQ #6 recommendations in our analysis we have to know how VL changes with the average light level. We assume that the lighting quality factors, contrast rendering, glare, and transient adaptation, are high and uncorrelated with average light level. We have set their correction factors, CRF, DGF and TAF, to 0.9, 1.0, and 1.0, respectively, in the analysis. As long as they are constant, the actual values turn out to be unimportant in this initial analysis.

Obviously, any real installation will have a distribution of CRFs, DGFs and TAFs. In a previous paper, we showed that a single value, the average of the logarithms, will give reasonable estimates of average performance.[13] We use the average because it is related to the overall productivity for situations where task locations and difficulties are not known in advance, and where the tasks are independent. This is the situation which is most common for tasks covered by RQQ #6. The averaging analysis above is not appropriate for situations where performance on one task depends upon the performance on previous tasks, so that the slowest link in the performance chain determines overall productivity as in an assembly line.

VLs can be measured or computed, so it will be possible for designers to do detailed cost-benefit analyses. At present software packages that calculate ESI assume that DGF and TAF are unity. Within this limitation VL is computed from ESI as follows:

$$VL(age,CRF,E) = VL(ref,1.0,E) * VL(age,1.0,E)/VL(ref,1.0,ESI) \qquad (5)$$

ESI is always calculated under reference age conditions (ref), which simply means that $LM = m_1 = 1$. The programs provide values of ESI and E, and the users select the age value appropriate to their problem.

Although VL is computed from ESI it does not share the problems of ESI. ESI is an expansive function of its parameters, VL a compressive one. Small errors in input give large errors in ESI[12], but the transform back to VL reduces them once again to small errors. Average ESIs may be meaningless, and ESI does not include information about task difficulty. The transformation to VL, and then performance, eliminates these difficulties, and gives results more in tune with experience.[13]

In this paper we use a log-normal function of VL to estimate visual performance, and then add a dilution factor to convert performance to productivity:

$$Productivity = W*Q(VL)/[mvf + (1-mvf)*Q(VL)] = W*Q(VL)/P(VL), \qquad (6)$$

P(VL) is defined by equation 6, W = A+B is the employee's maximum total worth, where A is the nonvisual portion, and B is the maximum visual portion of that worth

(B=mvf*W), mvf is the minimum visual fraction of the work, and Q(VL) is the relative visual performance log-normal:

$$Q(VL) = [1/\{\gamma*\sqrt{(2\pi)}\}] * \int_{-\infty}^{Ln(VL)} \exp[-0.5*\{(\chi-\alpha)/\gamma\}^2]\, dx, \tag{7}$$

where α is the mean of the Gaussian, and γ is its standard deviation.

We derive equation 6 by assuming that office visibilities are high enough that accuracy is, or could be, one, and that speed is the factor that affects productivity. Let t_n be the non-visual time, including the cognition and motor time, t_o the minimum time for the visual task, and Q(VL) the relative performance on the visual task. The total time to complete the task is $t_n + [t_o/Q(VL)]$. To get equation 6 divide the employee's worth by the total time, and substitute mvf = $t_o / (t_o + t_n)$.

Equations 6 and 7 were chosen because they have the right boundary conditions and general shape, they are simple and flexible, and involve a minimal number of free parameters. We are not claiming that the above function actually is the visibility-productivity function. Equation 7 in particular could be replaced with any smooth compressive function, including variants of Rea's. It is unlikely that any one function is correct for all work situations. Our claim is merely that equations 6 and 7 are constrained to have the right general shape, while retaining flexibility enough to provide a test of the RQQ recommendations. We have not chosen the complex CIE 19/2 VL-performance fit because we have shown in previous papers that it is logically flawed, many of the performance functions analyzed are poorly related to productivity, and it has no statistically valid advantage in fitting the data.[10,14]

An advantage of using a physically reasonable form such as equation 6 is that the unknowns have some physical meaning and thus can be bounded by external information. The minimum visual fraction, mvf, is by definition constrained to lie in the range from zero to one. The total worth of an employee must cover profit, rent, taxes, and so on, as well as salary. From company annual reports and other estimates, we estimate that salary is a half to a fourth of an employee's total worth.[15] Salaries can range anywhere from $8,000 to $500,000 per year, or more. Salary and mvf are probably negatively correlated, so B is likely to be more constant than either mvf or W. We assume that there is 10 m^2 of uniformly lit space per employee, or its non-uniformly lit equivalent, and that mvf varies from 5 to 60 percent. Our guess for B (in $/$m^2$-year) is that it may range from 1,000 to 10,000, with 2,000 to 5,000 being the most typical range. The log-normal unknowns are the hardest parameters to estimate from external information. In threshold detection experiments $\alpha = -0.9$, and $\gamma = 0.39$.[3] For more realistic complicated tasks their values seem to be higher, with α ® 0.7 to 1.0 and $\gamma \approx 0.5$ to 0.7. These are estimates based on a selection of the most easily interpretated data sets in CIE 19/2, and we take them as guidelines, not hard-bounds.

Results

Internal consistency of RQQ #6 recommendations

In RQQ #6 tasks are grouped by task difficulty. Categories A through C do not involve difficult tasks with well defined equivalent contrasts, $\tilde{C}$✎[1,3] For categories D through H task difficulty is given both by a written description and in terms of bounds on $\tilde{C}$✎ We used the middle value of $\tilde{C}$ and only analyzed these categories. Each category has three illuminance values. The value recommended depends upon three weight factors: age, reflectance and the importance of task speed and accuracy (which we henceforth refer to as task importance). A check for consistency with the RQQ recommendations is that when the weight factors and unknowns are specified the calculated optima are closer to the RQQ levels than the bordering levels, for all the tested illuminance categories. For example, for category E the illuminance levels are 500, 750, and 1000 lux. The reader will recall that our approximation for cost effective optimization is that the slope of the net-benefit equation be zero. Thus, if the recommended level is 750 lux the slope should be ≥ 0 at 625 lux (net benefit flat or increasing) and ≤ 0 at 875 lux (net benefit flat or decreasing).

The slope of the net-benefit curve, NB, follows from equations 1-7, and the text, and is given below:

$$\partial NB/\partial E = \partial[W^*Q(VL)/P(VL) - c^*E]/\partial E = (B/P(VL)^2)^{*}\text{⁕}\partial Q(VL)/\partial Ln(VL)]^*\partial Ln(VL)/\partial E - c \quad \text{(8a)}$$

$$= B^*\exp[-0.5^*\{(Ln(VL)-\alpha)/\gamma\}^2]/\{P(VL)^{2*}\gamma^*\sqrt{(2\text{❹})}^*E^*(1+\{E^*\rho^*LM/b\}^{0.4})\} - c, \quad \text{(8b)}$$

At the maximum the two unknowns, B and c, appear only as a ratio, so that there are effectively only four unknowns: B/c, mvf, α and γ✎ Figure 1 shows the results of a test of the inequalities described above at fixed values of mvf, and B/c (in units of lux), over a grid of values of α and γ✎ The enclosed area is a region in α✍γ space which fits the slope inequalities for categories D through H simultaneously. The existence of this region is an essential condition for self consistency in the RQQ levels. Note that the jaggedness of all our plots is an artefact of the coarseness of the grid search. All Greek symbols are spelled out in the figures.

Figure 1 only shows self-consistency of the RQQ levels over a fixed set of the weighting factors and economic parameters, B/c and mvf. To show overall self-consistency the α✍γ region shown in figure 1 should not be disturbed by reasonable changes in the other two parameters, or any of the weighting factors. If reasonable changes in the variables yield α✍γ regions which do not overlap with that in figure 1 then the RQQ recommendations are not economically optimal. Figures 2 - 8 explore these issues.

Figure 2 shows the consistency calculation with, and without the most difficult task level, category H. The consistency region for the first calculation is a subset of that of the latter calculation. The most difficult category is the one that puts the tightest constraints on the visibility parameters.

Figures 3 and 4 explore the effects of changing mvf and B/c respectively. The calculation is insensitive to mvf, but fails to maintain overlapping regions with changes in B/c. However, it seems reasonable that the RQQ task importance weight factor is related to changes in costs, c, or the value of visual work, B. Figure 5 shows that changes in the task importance factor partially match changes in B/c. A number of tests showed that the total range of the task importance factor is equivalent to about a factor of two in B/c.

Figure 6 shows that the reflectance weight factor does not totally compensate for the range of reflectances that it lists. Figures 7 and 8 show an even bigger disparity for the age factor. In figure 8 the B/c ratio was changed to test the hypothesis from CIE 19/2 that the maximum performance level has to be changed to fully account for the effects of age. The inconsistency, however, remains severe.

There are several general comments that are appropriate here. First, the visual performance levels implied by the consistency regions is fairly high, which is in accordance with the intent of the RQQ recommendations to apply to situations where visual performance is important. Second, the best match of the consistency region of α and γ to values found in visual performance experiments is for low values of mvf, which is not a problem, and high values of B/c. The ratio B/c is highest if first costs, and not life-cycle costs are used. The worry that designers were responding to first costs was a major reason for government intervention.

Net-benefit calculations

In this section we examine the economic consequences of any deviations between RQQ levels and the optimal levels. A base case is defined with fixed parameters: α = 0.86, γ = 0.31, weight factors: age = 47.5, and ρ = 0.75, and, a critical task with mvf = 0.2, and B/c = 200,000 lux. The base case is extended to different task importance levels by relating B/c to task importance. We fixed c at $0.01 per lumen year, and decreased B and mvf by a factor of ④2 for each step downward in task importance. These values assure a good match between the optimal economic levels, and the recommended levels, over the 15 conditions defined by the five task difficulty categories (D - H) and the three task importance levels. To examine the effect of different weight factors we defined variant cases that differ from the base case in only one parameter, or weight factor, such as can be seen in table 1.

For each condition we calculated the net benefit over the same pattern of discrete light level steps (200, 300, 500, 750 and so on) as was given in RQQ #6. A match between the RQQ recommended level and the light level which gives the maximum net benefit indicates that the RQQ level is economically optimal. When there is a mismatch we record the number of light level steps between the optimal and RQQ level to evaluate the size of the mismatch in terms of the light level recommendations. To evaluate the economic importance of the mismatch we look at the net benefit difference, and we compute a rate of return or loss (net-benefit difference per employee divided by the quantity {c * area/worker * light level difference}) to see if the investment in more (less) light is better than alternative investments.

Table 1 provides summary information on the above calculations for the base case, and six variant cases. The net loss column refers to the net benefit difference. The maximum columns are with respect to the 15 conditions for each case, and the average is calculated only over the mismatches found in a given case.

As expected the base case matches the RQQ #6 recommendations very closely. Cases 2 and 3 examine the consequences of B/c variations outside the narrow 2:1 range that is easily handled by the task importance factor. Case 3, shows that underestimating costs, and thus lighting more than is needed, can entail significant costs at fairly high rates of loss. Cases 4 and 5 show fairly small costs from mismatches from changes in reflectance. A wider range of reflectances would eventually make the losses large. Cases 6 and 7 show that the age mismatches can be very significant.

The economic losses are largest for more difficult weighting factors than the base case, and for the most difficult tasks. The optimal light levels are much higher than the recommended levels and the losses are determined by losses in productivity. For easy tasks the losses are due to the cost of overlighting, and thus tend to be much lower. Setting α and γ so that the recommended and optimal levels are matched for older workers lowers the maximum economic losses. It does not eliminate the mismatches. Tables 2 and 3 provide a look at the above patterns of losses.

In all we looked at base and associated variant cases for ten different pairs of α and γ, at several different values of c and mvf for each α✍γ pair. None of them were able to handle the full range of age, task importances, and to a lesser extent, reflectivities. We included one pair at $\alpha = 0.7$ and $\gamma = 0.5$, to match the visual performance experiment fits. It was worse than the pairs deliberately chosen to give a match versus task difficulty over a fixed set of weight factors.

In addition to not matching the pattern of the RQQ recommendations for the age factor, the performance fits predict substantially lower levels of performance for older workers on the more difficult visual tasks. Conceivably an older worker could find other ways to improve performance. For example, a magnifier would increase visibility, but decrease the field of view and thus lower the maximum attainable speed and productivity. We tested this alternate method hypothesis by running a fit with a slightly lower total worth, and a shift factor to increase $\tilde{C}$✎ The procedure worked for the older worker, but was too successful in that it also worked for younger workers. In one test we matched economically optimal light levels to the RQQ ones for the older workers, but found that young workers should also use the magnifier for tasks of difficulty level F and above. Their optimal light levels were 300, 750, 300, 750, and 1500 lux, with the drop occurring at category F. Thus, all the hypothesis does is move the problem of matching the RQQ recommendations from the older to the younger workers.

Discussion

In the above analysis we have chosen specific values for each of the RQQ weighting factors. Most situations will have a mix of ages, reflectances, and so on, and economic consequences of the mismatch between optimal and recommended levels will be less than was calculated for the individual cases above. The RQQ recommendations do not appear to be optimal over the full range of weighting factors that they are listed for. We will be examining the issue of mixtures of ages and tasks more closely in the future.

The implications of the apparent mismatch between our analysis and the IES recommendations must be considered in light of the fact that the IES recommendations are a consensus of what seems to work in the real world. It is fairly easy to tell when a lighting system is grossly inadequate (people complain), but it is less easy to tell if it is uneconomic due to too much light. This leads us to believe that the recommended ight levels are probably most accurate for the difficult visual conditions (low reflectance and older workers). Since our analysis indicates that the recommended levels cover a smaller range than is economic the implication is that lighting levels for younger workers should be lower than is presently recommended. Table 3 shows the costs associated with the assumption that the recommended levels are best matched to the older worker. The costs of overlighting in this case are fairly small for the less demanding categories D and E (not shown) that make up the bulk of office lighting. The costs are really only significant for the less common lighting situations covered by categories G and H.

On the other hand, if we take the position that the recommended levels are best matched to the middle age group, not only are we now dealing with underlighting, which is more apt to produce complaints, but the economic penalties are also higher. Table 2 shows these economic costs. The economic penalties are even high for the common office situations covered by category D. Because of the size, prevalence, and type of problem associated with the assumption that the recommended levels are best matched to the middle age group it seems unlikely that this assumption could be correct.

We did not show a table of costs for the assumption that the recommended levels are best matched to younger workers. It should be obvious, however, that these costs would be even larger than those shown in table 2. This assumption is thus even less tenable than the assumption that the recommended levels are matched to the middle aged group.

The costs in tables 2 and 3 were derived with a particular model, and would be different with a different model. On the other hand, the types of problems associated with underlighting and overlighting, discusssed above, are independant of the visibility model chosen for analysis. Underlighting is much more prone to cause complaints, and has higher potential costs. This means that it is much more likely that the recommended light levels are appropriate under moderately difficult visual conditions (older workers, and low reflectances) than they are under easy visual conditions. We will be extending our analysis in the future to see if different visibility models also predict that younger workers have more than the economically optimal amount of light.

Conclusion

We have used the RQQ #6 recommendations as estimates of optimum cost-effectiveness in order to fix unknown parameter values in a visual-performance based cost-benefit model. The consistency of the match is good over task difficulty levels ✈C̃✉, but fails on the weighting factors for age, task importance, and reflectivity. The RQQ recommendations appear to underestimate the importance of these factors to an economically significant extent. These conclusions appear robust, and will be checked against other models to see if they survive.

A significant result of the cost-benefit analysis, that is independent of the visual performance model used, is the identification of the weighting factor for the importance of speed and accuracy with the ratio of the the value of visual work to the cost of providing light. This term is not explicitly defined in the IES recommendations and is a source of potential confusion and ambiguity. The explicit definition shows that local differences in costs should be considered in evaluating this term. Our analysis also implies that the effect of differences in costs may be more important than is presently accounted for by the IES weighting factor. This is a quantitative argument that shows that costs should have a significant effect on lighting levels.

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Figure 1
Illuminance Categories and Illuminance Values
for Generic Types of Activities in Interiors

Type of Activity	Illuminance Category	Equivalent Constant $\tilde{C}$	Ranges of Illuminance Lux	Reference Work-Plane
Public spaces with dark surroundings	A	-	20-30-50	General lighting throughout spaces
Simple orientation for short temporary visits	B	-	50-75-100	
Working spaces where visual tasks are only occasionally performed	C	- 1.0	100-150-200 200	
Performance of visual tasks of high contrast or large size	D	.75-1.0	200-300-500	Illuminance on task
Performance of visual tasks of medium contrast or very small size	E	.62-.75	500-750-1000	
Performance of visual tasks of low contrast or very small size	F	.50-.62	1000-1500-2000	
Performance of visual tasks of low contrast and very small size over a prolonged period	G	.40-.50	2000-3000-5000	Illuminance on task, combination of general and local (supplmentary lighting)
Performance of very prolonged and exacting visual tasks	H	.30-.40	5000-7500-10000	
Performance of very special visual tasks of extremely low contrast and small size	I	under .30	10000-15000-20000	

If task reflectance is between 5 and 20 per cent use next higher illuminance category; i.e., D to E, E to F, etc. If less than 5 per cent use two categories higher.

Figure 2
Weighting Factors to be Considered in Selecting Specific Illuminance Within Ranges of Values for Each Category

a. For Illuminance Categories A through C

Room and Occupant Characteristics	Weighting Factor		
	-1	0	+1
Occupants ages	Under 40	40-55	Over 55
Room surface reflectances	Greater than 70 per cent	30 to 70 per cent	Less than 30 per cent

b. For Illuminance Categories D through I

Task and Worker Characteristics	Weighting Factor		
	-1	0	+1
Workers ages	Under 40	40-55	Over 55
Speed and/or accuracy	Not Important	Important	Critical
Room surface reflectances	Greater than 70 per cent	30 to 70 per cent	Less than 30 per cent